Current Trend in Optical Internet of Underwater Things

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Abstract—Our Earth is a "blue planet" that 70% of the surface is covered by the oceans, but most area of oceans remain largely unexplored. Besides supporting the Earth’s ecosystem and moderating climate change, oceans are rich in economically relevant natural resources ready for harvesting, such as fishery, oil and gas, and mineral resources. Ocean observation and monitoring are therefore essential for environmental preservation and sea exploration. With the availability of advanced communication techniques, researchers began to look into distributed data acquisition and ocean interconnectivity, which engendered the concepts of intelligent ocean and the Internet-of-Underwater-Things (IoUT) framework. The framework is gaining traction since one could incorporate fiber sensing, acoustic, radio frequency, and optical wireless communication technologies to establish stable, broad-coverage, and massive ocean networks. The development of underwater internet beyond acoustic communication is still in its relative infancy, and therefore more aggregated research efforts from the related communities will be required to eventually achieve breakthroughs in comprehensive IoUT technologies. This review sheds light on the practical considerations and solutions to the challenges and robustness of the optical IoUT network in terms of channel characterization, turbulence studies, mobility, receiver optimization, and the application layer.

Index Terms—Underwater wireless optical communication, underwater internet of things, sensor networks, underwater optical networks.

I. INTRODUCTION

UNDERWATER wireless communication becomes challenging in highly critical, unknown, and acrimonious oceans. Underwater acoustic communication is the primary technical means of wireless communication in the underwater channel to achieve broad coverage and connectivity. However, due to the limited bandwidth of acoustic waves (~kHz) and low propagation speed in the water, underwater acoustic communication technology has the disadvantages of small capacity, low data rate, large delay, and high bit error ratio (BER). These drawbacks cannot support large numbers of underwater nodes or mobile vehicles to carry out real-time, large-capacity, and high-speed data exchange. In the past decades, photoelectric composites cables—based submarine observation networks, as an essential part of Internet-of-Underwater-Things (IoUT), has played an important role in ocean monitoring applications [1], [2]. In the future, more autonomous underwater vehicles, gliders, and wireless sensor networks will be used to expand the submarine observation networks, thus establishing the wired and wireless IoUT. Under this context, we envisage the development of high-capacity, multi-hop networks that work in tandem with the wired counterpart. For realizing such a holistic approach, underwater wireless optical communication (UWOC) technology came into the picture. One could benefit from its high bandwidth, low latency, low power consumption, compactness, strong anti-interference ability, secure channel for real-time, high-speed (~Gbit/s), short distance (~100 meters) underwater wireless communication.

Most prior research on UWOC focused on the physical layer to improve the data rate and operating range [3]–[6]. In recent years, researchers have begun studying underwater link alignment, energy supply, and UWOC network subjects to implement high-availability and high-reliability optical IoUT [7]–[12]. For example, underwater dynamic factors, such as air bubbles, turbulence, and the mobile state of transmitters and receivers, may affect the link alignment of optical IoUT systems and thus degrade the communication performance. Therefore, scintillating fiber-based receivers with a large detection area has been proposed to be a promising solution [7]–[9]. Moreover, energy issues are becoming increasingly prominent in supporting the massive connectivity of various smart devices in IoUT [10]. In this case, solar cells with dual functions of signal acquisition and energy harvesting have been proposed as detectors in UWOC systems [11], [13]–[15]. To further promote the implementation of IoUT, underwater optical wireless sensor networks, and UWOC-based 2K real digital video surveillance have been studied experimentally [16], [17].

This review is structured as follows: Section 2 presents the comparison between underwater acoustic, RF, and optical communication technologies in IoUT and introduces the research progress of optical wireless communications and channel studies. The practical considerations and solutions to the challenges faced by the IoUT are discussed in Section 3. Section 4 focuses on the optical techniques for IoUT and demonstrates the real application scenarios in IoUT. Finally, Section 5 discusses the future directions of IoUT development before concluding the article.
II. OVERVIEW OF OPTICAL WIRELESS COMMUNICATIONS IN THE INTERNET OF UNDERWATER THINGS

A. Comparison between underwater acoustic, RF, and optical communication

Given the importance of exploring and studying oceanic environments, different technologies have been developed to allow wireless communication between monitoring nodes and base stations. Wireless communication can be achieved through acoustic or electromagnetic waves, including radio and optical frequencies. Together, these technologies enable tactical surveillance, offshore explorations, and oceanographic research, attracting great interest from the research community.

Acoustic communication is considered the most common and mature technique for underwater wireless information transfer [18]–[20]. The acoustic wave faces low attenuation in the water, which means the acoustic system can work over a range of kilometers [21]. With the development and verification of the underwater acoustic communication system, demand for underwater acoustic networks has risen. The technologies for networks, such as multiple inputs and multiple outputs [22], [23], medium access control [24], and underwater localization [25], [26], are required. Petrioli et al. demonstrated the SUNRISE GATE, which is used to facilitate the IoUT in 2014 [27]. Moreover, Alves et al. demonstrated the Littoral Ocean Observatory Network, which envisioned fostering cooperative development of underwater communications and networking [28]. Despite technological advancement, there are various hurdles to effective acoustic communication. Because of the frequency attenuation characteristics of the acoustic link in water, expanding the bandwidth of acoustic waves is difficult. Thus, the acoustic method can only achieve low data rates, with a maximum rate of tens to hundreds of kilobits per second [29]–[31]. Moreover, the time–varying multipath propagation and high latency impede the development of underwater acoustic communication [19].

The multipath phenomenon leads to pulse spread and results in inter–symbol interference, thus limiting the data rate [32], [33]. Furthermore, it is challenging to design low–cost, portable acoustic communication devices [34]. Finally, it is important to mention that acoustic–based wireless communication sources are one of the main noise pollution inducers in the ocean. They significantly affect the living environment of marine life.

Using an RF system for IoUT systems offers megabits per second (Mbit/s) data rate in water, which is much higher than the data rate of acoustic waves. However, the severe attenuation of RF in water constrains it to a few applications [35], [36]. The high conductivity of seawater induces the high frequency–dependent attenuation of RF waves [37]. When using extremely low frequency, ranging from 30 to 300 Hz, the system can work over a hundred meters [19]. Frater et al. found that the maximum working range for 100 kHz (10 kHz, and 1 kHz) waves is 6 m (16 m, and 22 m) [38]. Hence, RF waves are mainly employed for shallow water communication [39]–[41].

Because of acoustic and RF wireless communication limitations, UWOC has been under extensive research in recent years. Its main advantage is having a broad bandwidth while maintaining low latency, making it the key communication technology to realize real–time and high–speed IoUT [3], [4], [42]–[46]. The wide bandwidth is favorable for increasing the capacity of the optical communication system, which results in the possibility of building large–scale underwater sensor networks. Moreover, the high power efficiency lowers the cost of underwater communications. In addition, the difficulty of changing the battery in sensor nodes could potentially be solved by power–charging solar panels using a high–power laser during the periodic AUV visits [47]. Kong et al. achieved a high–speed UWOC system that can operate simultaneously with energy harvesting using a solar panel receiver [13]. Based on the above considerations, UWOC is a promising approach for underwater wireless communication that can work hand in hand with conventional technologies to expand the range of possible applications. Fig. 1 shows a comparison between different underwater wireless communication technologies regarding transmission distance and data rate [48], [49].

B. Progress of Optical Wireless Communication Development

The aquatic environment is considerably more vibrant and challenging than free space. Merely investigating how to improve the system’s data rate and working range is not enough to boost the UWOC system’s performance. The link configuration of the communication system impacts the data link and performance. Arnon did a survey that focused on the UWOC link configuration and its impact on the performance [50]. In this review, we demonstrated the link configuration studies, including diffuse–line–of–sight (DLOS) and non–line–of–sight (NLOS), in real scenarios and their impact on the performance of the optical IoUT systems. Since there is no universal type of underwater channel, there is no one–size–fits–all solution that can be used in all scenarios. For instance, the suspended infinitesimal particles and plankton in water absorb and scatter the light and thus cause loss of optical intensity [51], degrading the channel bandwidth and signal quality of UWOC systems [52]. Therefore, building a suitable IoUT system requires taking into account the light source type (light–emitting diode (LED) or laser diode (LD)), the used wavelength (mainly blue or green), the type of receiver, and signal processing aspects (which include the modulation scheme, error correction, and equalization techniques) [53], [54]. Johnson and Camila surveyed the channel model of UWOC systems since 2013 till 2017 [55]–[57]. In our review, we briefly introduced the basic channel model and channel characteristics and extended the study to channel turbulence.

In terms of modulation schemes, efficient and robust modulation schemes such as on–off keying (OOK) modulation [3], orthogonal frequency–division multiplexing (OFDM) [58], pulse–position modulation (PPM) [59], pulse–amplitude modulation [60], and discrete multitone with bit power loading [46] have been used to improve the achievable data rates. Previous surveys did by Zeng and Kaushal studied modulation schemes in UWOC systems [19], [52]. In this review, a comparison of OOK, PPM, and OFDM in terms of performance and robustness of the mobile optical IoUT system in real scenarios is reported in Section 3.
In terms of optoelectronic devices, highly sensitive photodetectors such as photomultiplier tubes (PMTs) [61], single-photon counters [62], silicon photo–multipliers [63], and multi–pixel photon counters (MPPCs) have been used for long–distance communication [59]. Beyond the comparison of optoelectronic receivers, section 3 of this review proposed the optical antenna design to extend the photodetector’s field of view (FOV) and active area for receiving photons. The optical waveguide placed in front of the photodetector can alleviate the alignment issue in the optical IoUT system.

C. Channel Modeling and Characteristic

Channel characterization is essential for the understanding of underwater optical channels. Scintillation of the received signal, the variations in the refractive index (RI) of the medium along the propagation path, and optical properties of the beam are the primary facets of channel modeling [64]. Johnson et al. reviewed the classic modeling approaches such as Beer Lambert’s law, the Monte Carlo (MC) method, and the radiative transfer function [65] and presented a comprehensive view of channel modeling. Smart [66], and Giles et al. [67] applied Beer Lambert’s law to assess the working distance of UWOC systems. Such studies focus on the effects of intrinsic optical properties (IOP), which are absorption and scattering, in static underwater channels. In addition, inherently time–variant turbulence effects degrade the performance of UWOC systems; oceanic turbulence induced by the fluctuations of temperature, salinity, and air bubbles have been studied for a better understanding of the underwater channel [68]–[72]. Nevertheless, research on dynamic underwater channels is more challenging than on static channels.

1) Absorption and Scattering Losses: Absorption and scattering are the main cause of power loss in UWOC channels [74]. A simple model to describe the principle of absorption and scattering is shown in Fig. 2. The rectangular water medium represents the unit of the underwater channel. After the incident optical beam \( P_i \) passes through the water unit, a fraction of the beam is absorbed \( P_a \), a fraction is scattered \( P_s \), and the remaining optical power \( P_R \) transmits through the unit unaffected and continues propagating. Therefore, the process can be described according to the conservation of energy [19] as follows:

\[
P_i = P_a + P_s + P_R
\]

(1)

Over a unit channel distance, the absorption coefficient is defined as the ratio of absorbed power to the incident power, and the scattering coefficient is defined as the ratio of scattered power to the absorbed power (given in \( m^{-1} \)):

\[
a = \frac{P_a}{P_i}, \quad b = \frac{P_s}{P_a}
\]

(2)

The overall attenuation coefficient, \( c \) is the sum of the absorption coefficient and the scattering coefficient. Since all these coefficients are wavelength–dependent in the same water medium, the expression is given as:

\[
c(\lambda) = a(\lambda) + b(\lambda)
\]

(3)

Typical values of \( a(\lambda) \), \( b(\lambda) \), and \( c(\lambda) \) at 520 nm in different types of water are listed in Table I [35]. The power path loss \( L \) of the optical beam after propagating a distance of \( z \) can be calculated by:

\[
L(\lambda, z) = e^{c(\lambda)z}
\]

(4)

2) Underwater Channel Turbulence: Besides the absorption and scattering, underwater turbulence is another crucial factor affecting underwater communication performance. The oceanic turbulence, such as bubble–, salinity–, and temperature–induced turbulence, results in variations of the RI of water.
[70], [72], [75]. The RI changes cause beam scintillation, affect the beam propagation direction, and cause alignment issues for optical IoUT systems [76]. Therefore, the oceanic turbulence engenders more complicated underwater channels, making turbulence studies necessary to develop optimal IoUT systems.

The work in [78] investigated the power loss under the effects of temperature variations in the channel. Furthermore, temperature-induced turbulence has been shown to have more significant effects on shorter wavelengths [79]. Besides temperature variations, fading effects brought about by the presence of air bubbles in underwater channels has also been studied in [75], [80]. It was observed that bubbles result in severe fluctuations of the received intensity, thereby causing a total loss of signal. Although Beam expansion increased the required transmit power, it obviously improved the UWOC communication performance by letting the bubbles partially block the beam. Statistical study in signal intensity fluctuation under bubble- and salinity-induced turbulence is conducted [81]. The fundamental reciprocal nature of all turbulence effects such as bubble-induced, temperature-induced, salinity-induced, and turbulent-flow-induced turbulence was validated [73], which can help provide real-time channel state information to the transmitter.

### III. RECENT ADVANCES IN TESTBED STUDIES

Creating different water types can ease the requirement of in-situ testing of the optical systems. Therefore, many researchers have capitalized on laboratory testbeds to confirm their hypothesis in multidisciplinary areas such as error correction schemes and enhanced modulation formats, or even the performance of the optoelectronic devices such as blue gallium nitride μLED [99]. The leverage of simulating and controlling different parameters such as the water turbidity and underwater turbulence also allows the estimation of the link budget and the operational distances for the optical IoUT prototypes. For example, the work in [102] utilized different water types to confirm the feasibility of NLOS communication, which otherwise would be challenging to perform in the natural environment, as shown in 3(a). In addition, the resilience of NLOS communication against turbulence effects such as thermal, salinity, and air bubbles was proven in prior studies [93], [103]–[105]. Another testbed study delivered a real-time full-duplex (FD) UWOC prototype utilizing a field-programmable gate array (FPGA) module to achieve the video streaming feature in an indoor 10–m laboratory tank using frequency shift keying modulation [95]. While capitalizing on advanced hardware such as FPGA, the study in [101] demonstrated a high-speed UWOC system using multicarrier modulation format to realize 50 Mbit/s data rate in a laboratory experiment. To exploit the capability of encoding data on different wavelengths of light, wavelength division multiplexing was utilized to realize a record-high data rate of 100 Gbit/s [100]. However, owing to the limitation of increased pointing requirements due to the wavelengths isolation at the receiver, the work in [8] demonstrated a WDM receiver using scintillating fibers to achieve the omnidirectional detection feature.

Apart from the conventional signal propagation route, where both the transmitter and receiver are submerged in the water, the water-to-air modality have been excessively studied in the literature due to its tremendous advantages [96]. However, due to the naturally challenging optical link arising from the dynamic wavy surface, dedicated testbeds have investigated wave mitigation techniques using beam tracking [97] and corrective advanced signal processing [98].

### A. NLOS-based optical IoUT System Under Turbulence

Due to the complex underwater terrain and channel environment, it is challenging to meet the strict alignment requirement of the LOS IoUT systems. The NLOS link configuration in IoUT can mitigate the pointing–acquisition–tracking (PAT) issues in the LOS link configuration by offering a viable path in signal propagation and coverage. In addition, because of the low background solar radiation and low device dark noise in UV-band, especially in the UV-C/B band (100-280 nm) [82], UV-based communication links are subject to low background noise [83] which allows the utilization of highly sensitive photo-detectors such as PMT and MPPC. However, implementing the NLOS link is non-trivial. The associated path-loss in the NLOS is significant as it relies on light scattering or the reflection of the dynamic water-air interface. Therefore, there have been considerable research efforts on the two configurations of NLOS; either by directing the transmitting beam at an arbitrary elevation angles and rely on the scattered photons to reach the receiver, or by directing the transmitting beam towards the water surface to encounter total internal reflection towards the receiver end.

Analytical and simulation approaches were first taken in the literature to verify the feasibility of NLOS-based configuration. Arnon et al. proposed a closed-form model of reflective NLOS and studied the dependence of BER on the nodes’ separation distance [84]. The pathloss of reflective NLOS was evaluated using Monte Carlo simulation to reveal the strong dependence with surface slope as a result of wind induction [85]. To facilitate the effect of surface waves, the work in [86] used optical adaptive-feedback to correct for the transmitted beam profile. However, their proposition may not be practical at the time being. The study in [87] showed that a wavelength of 490 nm is the must suited for the reflective configuration. However, this can compromise the transmission distance, which requires a cooperative transmission using relay and forward technique that may increase the system complexity due to the power allocation and optimization [88].

<table>
<thead>
<tr>
<th>Water Type</th>
<th>a (m⁻¹)</th>
<th>b (m⁻¹)</th>
<th>c (m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Ocean</td>
<td>0.114</td>
<td>0.037</td>
<td>0.151</td>
</tr>
<tr>
<td>Coastal Ocean</td>
<td>0.179</td>
<td>0.220</td>
<td>0.339</td>
</tr>
<tr>
<td>Turbid Harbor</td>
<td>0.336</td>
<td>1.829</td>
<td>2.195</td>
</tr>
</tbody>
</table>

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As far as experimental trials are concerned, a recent study demonstrated 300 Mbit/s transmission using reflective NLOS with varying surface wave frequencies [89]. However, the study did not consider practical factors such as random surface wave, the effect of divergence angles and scintillation mitigation methods, which leaves room for further research.

On the other hand, scattering-based NLOS received greater research exposure in the literature due to its convenience in relaxing the PAT requirements. Because it relies on the scattered photons, the channel impulse response was evaluated at different wavelengths, receiver FoVs, and water types to estimate the transmission distance and the available transmission rate of the channel [90], [91]. It was estimated that NLOS can operate at moderate distance of up to 100–m for short–range and robust communication [92].

The practical enviroment, the underwater turbulence can severely affect the LOS communication. In contrary, the underwater turbulence enhances the scattering effects which can facilitate the NLOS communication. Therefore, increasing the scattering elements (Rayleigh scattering) such as salt contents and air bubbles can increase the redirected photons towards the receiver. To investigate the impact of air bubbles induced turbulence, a typical experimental testbed can be conducted as in Fig 4(a), where the transmitter and the receiver are parallel to each other. Due to the scintillation of the received power as a result of the scattering events from the air bubbles, we can build a relationship between the scintillation index and the normalized received power. It can be seen from Fig. 4(b) that a strong linear correlation appears between the scintillation index, the normalized received power as the mean bubble area increases. Consequently, leading to the conclusion that NLOS is a robust modality against air bubbles-induced turbulence [93].

Salinity turbulence in the underwater channel can cause variations in the water medium’s refractive index. This variation changes the beam propagation direction and causes power loss during the propagation. Salt elements in water, such as NaCl, MgCl, and MgSO4, make the principal contributions to the absorption of signal in the water [106]. Researchers hypothesized that salinity–induced turbulence enhances NLOS communication by predominantly enhancing the scattering events in the aquatic channel [93], [103]–[105].

![Fig. 4(c) shows the experimental setup for the NLOS UWOC performance enhancement study under vertical–gradient salinity [93].](image)

<table>
<thead>
<tr>
<th>Modality</th>
<th>Modulation scheme</th>
<th>Transmission Distance</th>
<th>Data Rate</th>
<th>Transmitter</th>
<th>Receiver</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLOS</td>
<td>NRZ–OOK (PRBS-210,1)</td>
<td>43 cm</td>
<td>80 Mbit/s</td>
<td>377 nm LD</td>
<td>PMT</td>
<td>[93]</td>
</tr>
<tr>
<td>NLOS</td>
<td>NRZ–OOK (PRBS-210,1)</td>
<td>30 cm</td>
<td>85 Mbit/s</td>
<td>377 nm LD</td>
<td>PMT</td>
<td>[94]</td>
</tr>
<tr>
<td>NLOS</td>
<td>video transmission</td>
<td>10 m</td>
<td>1 Mbit/s</td>
<td>450 nm LED</td>
<td>APD</td>
<td>[95]</td>
</tr>
<tr>
<td>DLOS</td>
<td>8-QAM OFDM</td>
<td>30 cm, 60 cm water</td>
<td>1114 Mbit/s</td>
<td>350 nm LED</td>
<td>APD</td>
<td>[96]</td>
</tr>
<tr>
<td>DLOS</td>
<td>8-QAM OFDM</td>
<td>0.14 m, 1.2 m air</td>
<td>1.25 Gbit/s</td>
<td>450 nm LD</td>
<td>APD</td>
<td>[97]</td>
</tr>
<tr>
<td>DLOS</td>
<td>GS-8-QAM OFDM</td>
<td>3.6 m, 8 m air</td>
<td>2.2 Gbit/s</td>
<td>450 nm LD</td>
<td>APD</td>
<td>[98]</td>
</tr>
<tr>
<td>DLOS</td>
<td>GS-8-QAM OFDM</td>
<td>2.3 m</td>
<td>933 Mbit/s</td>
<td>440 nm microLED</td>
<td>APD</td>
<td>[99]</td>
</tr>
<tr>
<td>DLOS</td>
<td>WDM PAM4</td>
<td>500 m, 5 m water</td>
<td>100 Gbit/s</td>
<td>405 nm and 450 nm LD</td>
<td>Photodiode</td>
<td>[100]</td>
</tr>
<tr>
<td>DLOS</td>
<td>16-QAM OFDM</td>
<td>3 m</td>
<td>85 Mbit/s</td>
<td>450 nm LD</td>
<td>Photodiode</td>
<td>[101]</td>
</tr>
</tbody>
</table>
The DLOS configuration mitigates the instability of communication links caused by the motion of systems. This configuration was also proposed to be applied in cross water/air interface optical communications [96], [110]. The DLOS–configuration–based optical wireless communication can help to solve the connectivity issues between the undersea sensors and airborne nodes across the water–to–air interface (shown in Fig. 7). The system features alignment and user mobility challenges and facilitates a 44–Mbit/s communication link over 2.3–m underwater channel and 3.5–m air channel in the mobile case. The large illumination area of the DLOS configuration brings large signal coverage. DLOS helps overcome the inter–symbol interference from the channel uncertainty. This mitigation strategy is favorable in harsh environments for robust communication links. Hardships in the ROV and drone control (holding positions and precise movement control) result in taking a long time to set up communication connections. Maintaining communication connection is not trivial, either. In a dynamic underwater channel, a large illumination area can alleviate the PAT issues in communication link alignment and
In recent years, more and more underwater gliders, AUVs, and underwater wireless sensor networks (UWSNs) have been deployed in marine environmental monitoring and resource exploration. The amount of data that needs to be collected and processed increases exponentially, as does the amount of energy that needs to be fed to various underwater mobile devices. Hence, to improve energy efficiency and extend the operational life of these devices, energy-autonomous approaches are gaining increasing attention. Kang et al. firstly proposed to use ultraviolet-to-blue color-converting plastic scintillating fibers with large-area, and wide-angle-of-view as a photoreceiver in an underwater environment to ease the strict PAT requirements. The working principle of scintillating fibers in signal detection is illustrated in Fig. 8. A data rate of 250 Mbit/s was achieved with low outage probabilities over a 1.5-m underwater channel with different turbulence-induced fading, including air bubbles, salinity, temperature, turbidity, and mobility. Moreover, a 7.5-m transmission distance in the stationary case and a 1-m transmission distance in the mobile case were achieved with a data rate of 250 Mbit/s and 0% outage probability in an outdoor diving pool. This proves the robustness of the scintillating fiber-based UWOC system. In [9], to further improve the data rate, two bundles of scintillating fibers emitting wavelengths at 430 nm and 488 nm were used to detect two independent on-off keying signals from 405 nm and 450 nm laser sources, respectively, as shown in Fig. 8(b, e). An optical filter was placed between two fiber bundles to reduce the crosstalk and interference between two signals. A zero-forcing equalization approach was employed to minimize crosstalk as well. The aggregate data rate of 1 Gbit/s was achieved through this method.

Using ultra-sensitive optical sensors is not the only way to improve the optical IoUT system’s working distance and ease the PAT issues. Optical waveguide design, aperture optimization, and many other means are waiting to be explored to optimize the receiver design in the optical IoUT system and alleviate underwater link alignment issues.

IV. PROTOTYPE DEPLOYMENTS IN EMULATED ENVIRONMENTS

Based on the extensive testbed studies conducted over the years, researchers have started testing self-contained prototypes of optical communication systems in outdoor environments. These underwater optical modems have been developed by MIT Lincoln Lab [108], Woods Hole Oceanographic Institution (WHOI) [113], Sonardyne [119], etc.(listed in Table III), which are tested in environments varying from outdoor pools to seawater (In the table, WHOI: Woods Woods Hole Oceanographic Institution; Univ.: University; MIT: Massachusetts Institute of Technology; KAUST: King Abdullah University of Science and Technology.). To run these experiments, the developed systems need to meet specific criteria in terms of size and the ability to process and store data. This section reviews some of the recent prototype deployments we developed, summarized in Fig. 9.

A. Toward Energy-autonomous IoUT

In recent years, more and more underwater gliders, AUVs, and underwater wireless sensor networks (UWSNs) have been deployed in marine environmental monitoring and resource exploration. The amount of data that needs to be collected and processed increases exponentially, as does the amount of energy that needs to be fed to various underwater mobile devices. Hence, to improve energy efficiency and extend the operational life of these devices, energy-autonomous approaches are gaining increasing attention. Kang et al. firstly proposed to use ultraviolet-to-blue color-converting plastic scintillating fibers with large-area, and wide-angle-of-view as a photoreceiver in an underwater environment to ease the strict PAT requirements. The working principle of scintillating fibers in signal detection is illustrated in Fig. 8. A data rate of 250 Mbit/s was achieved with low outage probabilities over a 1.5-m underwater channel with different turbulence-induced fading, including air bubbles, salinity, temperature, turbidity, and mobility. Moreover, a 7.5-m transmission distance in the stationary case and a 1-m transmission distance in the mobile case were achieved with a data rate of 250 Mbit/s and 0% outage probability in an outdoor diving pool. This proves the robustness of the scintillating fiber-based UWOC system. In [9], to further improve the data rate, two bundles of scintillating fibers emitting wavelengths at 430 nm and 488 nm were used to detect two independent on-off keying signals from 405 nm and 450 nm laser sources, respectively, as shown in Fig. 8(b, e). An optical filter was placed between two fiber bundles to reduce the crosstalk and interference between two signals. A zero-forcing equalization approach was employed to minimize crosstalk as well. The aggregate data rate of 1 Gbit/s was achieved through this method.

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equipment and their signal processing units. However, the electrical power provided to underwater mobile equipment and wireless sensor network nodes is usually limited, and it is physically challenging to charge or replace batteries underwater. Due to these reasons, the transmission power of the transmitter in the optical IoUT system is restricted to ensure a sustainable and long operating period. Another reason for the optical power limitations on the transmitter is that the high–power optical illumination may affect the marine mammal’s habitat. Safety issues to both human and marine life must be considered, which limits the device choice and power of the transmitter and thus limits the working distance, FOV, and performance of the IoUT. In this context, the problem of underwater power supply has become an important factor restricting the development of underwater mobile equipment and technology. To alleviate underwater energy-shortage issues, solar cells used as detectors for simultaneous energy harvesting and signal detection have been mooted as a promising solution.

In [11], a solar cell with a large receiving area and lens-free operation were first proposed and used as a photodetector to alleviate link alignment and energy-shortage issues in complex underwater optical channels. The 22.56–Mbit/s OFDM signals were successfully transmitted over a 7-m tap water channel and emulated turbid water. In [13], Kong et al. demonstrated an amorphous silicon solar cell receiver (named AquaE–lite I, as shown in Fig. 9(a)) with a large detection area. The AquaE–lite I’s unique advantage is its high absorption coefficient from the visible to the near-infrared spectrum, enabling weak-light detection and energy harvesting in the dynamic underwater environment. A data rate of 1 Mbit/s signal over a 20–m transmission distance was realized in a laboratory testbed, and a data rate of 908.2 kbit/s over a 2.4–m transmission distance was realized in an outdoor diving pool, both under conditions of strong background sunlight. In addition, amorphous silicon solar cells with translucent and flexible properties were proposed to be integrated into underwater robots and underwater wireless sensor network nodes to realize self–powered IoUT in the future.

In [14], to achieve an integrated system with efficient underwater energy acquisition and weak–light signal detection,
a hybrid solar cell receiver, named AquaE-lite II, as shown in Fig. 9(b), was developed. The AquaE-lite II fully uses the advantages of different cells: the amorphous silicon solar cells with high absorption coefficient were used for weak-light signal detection, while monocrystalline silicon solar cells with high photoelectric conversion efficiency were used for optical energy harvesting. A 1.2-Mbit/s data rate and a 30-m transmission distance were realized using the amorphous silicon solar cells on a laboratory testbed. In the outdoor environment, the energy collected by the monocrystalline silicon solar cells was enough to power the receiver circuit, thus supporting the communication of the amorphous silicon solar cells with a data rate of 1.2 Mbit/s over a distance of 15 m. To verify the effectiveness of amorphous silicon solar cells in underwater weak-light detection and solving underwater link alignment issues, transmission distances of 1 m and 2 m were achieved without accurate alignment in a harbor [14] and a canal [10] of the Red Sea.

Besides these prototypes, a implemented simultaneous optical signal and power transfer system is reported [15]. Using a 430-nm laser, it took about 120 minutes to charge an 840-mW submerged module, which employed solar cells for energy harvesting. It can support a temperature sensor on the submerged module to work for more than 120 minutes. Moreover, 100-kHz commands at a data rate of 500 kbit/s were archived using the blue laser and the solar cell over a 1.5-m underwater channel. Using a 4.8-W LED took about 90 minutes to change a supercapacitor on an IoUT device. It can support an analog camera equipped on the IoUT device to transmit 1-minute-long real-time video streaming over a 30-cm underwater channel.

**B. Toward Real-time and High-speed IoUT**

UWOC technology is expected to become an essential communication means in the future underwater human-robot interaction and optical IoUT applications. However, there are only a few theoretical and simulation studies on UWOC network implementation [120]–[122]. In [16], the first optical-based UWSN prototype, named AquaE-net (as shown in Fig. 9(c)), was developed, which consists of an optical hub, two sensor nodes, and a real-time monitoring software platform for shore-based stations. The sensor node comprised a transceiver circuit, a pH sensor, and an integrated temperature, salinity, and conductivity sensor. These nodes were designed to allow underwater environmental monitoring in real-time. The optical hub was equipped with four transceivers facing a specific direction to enable FD communication with the sensing nodes. The real-time monitoring software platform used in the optical hub in shore-based stations can remotely control the parameters of the sensing nodes. Generally, sensor nodes of UWSNs suffer from the limited available power and even pose challenges in replacing batteries. Therefore, it was imperative to carefully consider Open Systems Interconnection layers and many practical application factors, including power consumption, data rate, transmission distance, link alignment issues, real underwater environment, etc. The optical base station and sensor network nodes were powered by only f 18650 batteries to support their continuous operation for about five hours. In turbid Red Sea port water, a data rate of 1.5 Mbit/s and a transmission distance of 0.6 m were achieved without accurate link alignment. This demonstration represents the first step toward future real-time and high-speed IoUT.

**C. Toward High Visual-Fidelity IoUT**

In recent years, to realize real-time and high-resolution digital video surveillance in the future underwater wireless sensor network, researchers have begun to pay close attention to studying multimedia transmission systems based on UWOC. Since 2005, researchers have explored underwater optical multimedia transmission [113], [123]–[125]. More recently, a series of quantitative studies on underwater optical video transmission performed on laboratory testbeds have been carried out [95], [126]–[131]. In [128], high-resolution (4096 × 1762 pixels) video transmission was implemented in emulated seawater on a laboratory testbed using high-bandwidth laser diodes and laboratory equipment and a spectrally-efficient OFDM modulation scheme. In [17], we developed a real-time 2K (1920×1080 pixels) digital video surveillance prototype based on UWOC (named AquaF-seer, as shown in Fig. 9(d)). A 3-W LED with a large divergence angle as the transmitter and an avalanche photodiode as the receiver were used to investigate the effects of different underwater channel environments on the image quality and real-time 2K digital video transmission over a 1.5-m water tank with different turbidity and bubbles. Real-time 2K digital video surveillance has been achieved in a 46-m indoor free-space channel and a 5-m outdoor diving pool channel. This work represents the highest resolution achieved in a real-time digital video surveillance system using UWOC based on FPGA, a single low-modulation bandwidth LED, and a simple modulation scheme (OOK) so far. This paves the way for future real-time, dynamic, and visual monitoring of underwater scenes in human-robot interaction applications. In the future, transmitter...
Fig. 8. Illustration of the working principle of (a) scintillating fibers and (b) scintillating fibers used in WDM receivers. (c) and (d) are examples of detectors based on scintillating fibers [7] [8]. (e) Example of WDM scintillating fibers receivers [9].

Underwater Wireless Optical Communication Prototypes

<table>
<thead>
<tr>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
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<tbody>
<tr>
<td>AquaE-lite I</td>
<td>AquaE-lite II</td>
<td>AquaE-net</td>
<td>AquaF-seer</td>
</tr>
<tr>
<td>Lens-free solar-cell receiver based on amorphous silicon</td>
<td>Amorphous silicon for signal detection and monocrystalline silicon for energy harvesting</td>
<td>Underwater optical wireless sensor network prototype (1 hub and 2 nodes)</td>
<td>Digital video surveillance prototype</td>
</tr>
<tr>
<td>• 0.9-Mb/s data rate</td>
<td>• 1.2-Mb/s data rate</td>
<td>• 1.5-Mb/s data rate</td>
<td>• 2K resolution live streaming</td>
</tr>
<tr>
<td>• 2.4-m diving pool link</td>
<td>• 2.0-m canal link in the Red Sea</td>
<td>• 0.6-m turbid sea water channel</td>
<td>• 5-m diving pool link</td>
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Fig. 9. A list of recent prototype deployments in underwater environments. (a) An amorphous silicon solar cell receiver [13]. (b) A hybrid solar cell system to achieve optimal energy harvesting and signal detection [14]. (c) The first optical based underwater wireless sensor network prototype [16]. (d) Real-time digital video surveillance prototype [17].

and receiver innovations, higher speed devices, and advanced modulation schemes can improve the data rate to support more applications of IoUT under different scenarios.

V. Future Directions and Conclusions

To promote the application of IoUT in the future optical—acoustic—radio–frequency hybrid mobile communication network based on underwater robots, it is necessary to develop
novel IoUT protocols in terms of the characteristics of both complex optical channels and cooperative operation of underwater robots. Current research focuses on the centralized routing network but lacks the study of distributed and dynamic routing networks. For example, it is necessary to study different network topologies (single-hop and multi-hop topology) for different application scenarios. As UWOC is characterized by solid directivity and short transmission distance, it is pretty interesting to develop novel distributed and dynamic routing algorithms to improve the coverage of IoUT and makes it can adapt itself according to the environment. To further improve the availability and reliability of optical IoUT, it is of great significance to design a cross-layer optimization framework based on physical layer parameters that can adapt to different channel conditions and dynamically changing routing paths. The energy-hungry issues mentioned in the previous section shows the limited energy resources for underwater optical sensor nodes. Taking the monetary cost of battery replacement into account, making IoUT system energy self-sufficient is necessary but challenging. The energy harvesting technologies aim at the aquatic environment are not enough. Designing energy harvesting protocols for IoUT is in infancy and in demand.

In addition to optical—acoustic—radio—frequency hybrid mobile communication network, the fusion of fixed seabed observation network based on optical fiber and mobile seabed observation network based on the wireless network is also an interesting and meaningful research direction. The existing fixed seabed observation network based on optical fiber has played an essential role in an oceanographic observatory, seismic monitoring, environment monitoring, and deep-sea ecosystem and biodiversity studies. In the future, hybrid fiber—optic communication and distributed sensing technologies are expected to build large-scale underwater sensor networks capable of realizing simultaneous ocean data transfer and real-time ocean monitoring. Moreover, the fusion of fixed seabed observation networks based on optical fiber and mobile seabed observation networks based on the wireless network will greatly promote the development of IoUT.

The recent developments in optical IoUT technology can lead to the proliferation of smart interconnected underwater sensor notes with networks consisting of fiber sensing, acoustic, RF, and optical wireless communications. Towards establishing stable, low-cost, robust, and high-speed smart ocean networks, the underwater channel characterization, channel turbulence effects, the robustness of communication links in mobile nodes, communication configurations, receiver optimization to relieve the PAT issues, and fusion of application layer of optical IoUT were discussed. There is a dire need to implement the practical IoUT system. We envision that the optical IoUT worldwide network can eventually lead to a Smart Ocean era. Finally, numerous open challenges and future directions were presented, opening the doors to explore new ocean monitoring and ocean explorations applications.

REFERENCES